

ORIGINAL RESEARCH

THE ASSOCIATIONS BETWEEN HIP STRENGTH AND HIP KINEMATICS DURING A SINGLE LEG HOP IN RECREATIONAL ATHLETES POST ACL RECONSTRUCTION COMPARED TO HEALTHY CONTROLS

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ABSTRACT

Background: Only a small amount of evidence exists linking hip abductor weakness to dynamic knee valgus during static and dynamic activities. The associations of hip extensor strength and hip kinematics during the landing of a single leg hop are not known.

Purpose: To determine if relationships exist between hip extensor and abductor strength and hip kinematics in both involved and uninvolved limb during the landing phase of a single leg hop in recreational athletes post anterior cruciate ligament (ACL) reconstruction. The presence of similar associations was also evaluated in healthy recreational athletes.

Study Design: Controlled Laboratory Study; Cross-sectional

Methods: Twenty-four recreational college-aged athletes participated in the study (12 post ACL reconstruction; 12 healthy controls). Sagittal and frontal plane hip kinematic data were collected for five trials during the landing of a single leg hop. Hip extensor and abductor isometric force production was measured using a hand-held dynamometer and normalized to participants' height and weight. Dependent and independent t-tests were used to analyze for any potential differences in hip strength or kinematics within and between groups, respectively. Pearson's r was used to demonstrate potential associations between hip strength and hip kinematics for both limbs in the ACL group and the right limb in the healthy control group.

Results: Independent t-tests revealed that participants post ACL reconstruction exhibited less hip extensor strength (0.18 N/Ht*BW vs. 0.25 N/Ht*BW, $p < .01$) and landed with greater hip adduction (9.0° vs. 0.8°, $p < .01$) compared with their healthy counterparts. In the ACL group, Pearson's r demonstrated a moderate and indirect relationship ($r = -.62$, $p = .03$) between hip extensor strength and maximum hip abduction/adduction angle in the involved limb. A moderate and direct relationship between hip abductor strength and maximum hip flexion angle was demonstrated in the both the involved ($r = .62$) and uninvolved limb ($r = .65$, $p = .02$). No significant associations were demonstrated between hip extensor or abductor strength and hip flexion and/or abduction/adduction angles in the healthy group.

Conclusion: The results suggest that hip extensors may play a role in minimizing hip adduction in the involved limb while the hip abductors seem to play a role in facilitating hip flexion during the landing phase of a single leg hop for both limbs following ACL reconstruction. Researchers and clinicians alike should consider the importance of the hip extensors in playing a more prominent role in contributing to frontal plane motion.

Levels of Evidence: Level 2a

Keywords: ACL reconstruction, hip strength, kinematics, single leg hop

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INTRODUCTION

An estimated 200,000 people suffer an anterior cruciate ligament (ACL) injury each year.¹ Further evidence suggests that only 70% will return back to their previous level of function.² For those that do return to sport, approximately 30% will be at risk of suffering a subsequent ACL injury to either the contralateral limb or ipsilateral limb.³ The majority of ACL injuries have been attributed to noncontact mechanisms during sudden decelerations and jump-landings.^{4,5} Risk factors associated with noncontact ACL injuries have been classified as environmental, anatomical, hormonal, or biomechanical.^{6,7} Of these four risk factors, biomechanical factors have received the most attention since they are likely the easiest to change through neuromuscular training.⁸ In particular, excessive knee valgus during dynamic activities involving jump-landings and cutting has received the most attention due to its link to ACL (re)injury.⁹⁻¹¹

A recent evidence-based review has highlighted the value of hip-specific neuromuscular exercise interventions that are capable of modifying dynamic knee valgus in efforts to prevent anterior cruciate ligament (ACL) injuries.¹² Separate studies by Leetun¹³ and Nadler¹⁴ demonstrated that female athletes who experienced lower extremity injury were more likely to demonstrate decreased hip strength. Howard et al¹⁵ demonstrated that weakness of the hip abductors and external rotators was associated with increased knee valgus during single-leg landing tasks. This line of research has shown a possible association between weak hip abductors and excessive valgus motion at the knee.¹⁶ However, a recent systematic review demonstrated only a small amount of evidence linking hip abductor weakness to dynamic knee valgus.¹⁷ Previous studies tended to only analyze either hip abductor and/or external rotator strength.¹⁸⁻²⁵ Therefore, researchers and clinicians alike may have focused primarily on hip abductor and external rotator strength and overlooked the capability of the hip extensors to provide dynamic stability within the frontal plane. For this reason, it would be of interest to know if potential associations between hip extensor strength and hip kinematics exist during dynamic movements in individuals who have undergone ACL reconstruction as well as healthy athletes.

The single leg hop test is frequently used by clinicians to assess functional performance after ACL reconstruction to determine readiness to return to athletics.^{26,27} In particular, Engelen-van Melick et al²⁷ demonstrated that the single leg hop is the most frequent measurement used to assess patients' function more than two years after ACL reconstruction. Trigsted et al²⁸ demonstrated less maximal knee flexion in the involved limb during the landing phase of a single leg hop in individuals who had returned to sport following ACL reconstruction compared to healthy controls. Xergia et al²⁹ further demonstrated that individuals after ACL reconstruction landed with greater hip flexion on the involved limb compared to healthy controls. These studies highlight the continued asymmetries that exist in athletes after ACL reconstruction despite these individuals having returned to sport.

A recent systematic review demonstrated that knee extensor and flexor weakness along with hip extensor weakness is typical following ACL reconstruction and may persist for two years or more.³⁰ Knee extensor and flexor strength deficits were associated with graft choice, indicating that extensor weakness is more common with patellar tendon grafts, while knee flexor weakness is associated with hamstring grafts. These altered biomechanics in landing when compared to the uninvolved limb can be directly attributed to these weaknesses.^{22,31,32} For example, Oberlander et al³² revealed that 78% of the extensor knee joint moment variability during the landing phase of a single leg hop at 12 months following ACL reconstruction was explained by the strength of the knee extensors. It remains unknown if hip extensor weakness would result in similar compensatory patterns in individuals post ACL reconstruction when performing dynamic landing activities, such as a single leg hop.

Therefore, the primary purpose of this study was to determine if relationships exist between hip extensors (primarily gluteus maximus) and maximum hip flexion and/or abduction/adduction during the landing phase of a single leg hop in both the involved and uninvolved limb of recreational athletes post ACL reconstruction and also in healthy controls. A secondary purpose was to determine if relationships exist between hip abductors and maximum hip

flexion and/or abduction/adduction as well. It was hypothesized that both groups would both exhibit significant associations between hip strength and hip kinematics during the landing phase of a single leg hop.

METHODS

Participants and Screening

Recreational athletes from 18 to 30 years old who had undergone unilateral ACL reconstruction, completed formal rehabilitation, and released by their physician to return to sport or activity were recruited via university email. A secondary group of healthy, recreational athletes was recruited from a population of convenience from the physical therapy program and matched to participants in the ACL group based on gender and activity level. Additional inclusion criteria required that participants in both groups were currently active in a sport or recreational activity a minimum of 2x/week for at least 30 minutes and participated in a jumping or cutting activity at least 1x/month. Participants in the ACL reconstruction group were excluded if they had any other knee ligament injury requiring surgical repair. Participants were excluded from the healthy, recreational athlete group if they had a history of lower extremity surgery. Participants in both groups were excluded if they had scoliosis, limb length inequality, or history of low back pain or lower extremity injury in the prior six months that limited activity for more than two weeks.

All procedures were approved by the Institutional Review Board at the University of Tennessee at Chattanooga and all participants provided written informed consent to participate. All participants who met the inclusion criteria were screened for the presence of a limb length inequality or scoliosis. Participants were instructed to wear athletic shoes, shorts, and a t-shirt for the screening. Limb length inequality was assessed using an indirect method³³, while scoliosis was assessed using the forward bend test³⁴ by a licensed physical therapist with 16 years of experience in outpatient orthopaedics. Any participant with a limb length inequality > 6.4 mm or having a positive forward bend test was excluded as both limb length inequality and scoliosis have the potential to affect hip posture and hip kinematics.

Participants' height and weight were measured using a standard scale. The single leg hop for distance³⁵ was also assessed for each limb, averaging three successful attempts. Participants were allowed free movement of their upper extremities during this single leg hop. Any participant who was unable to jump a distance of at least 75% of their height was excluded. This standardized distance requirement was adopted because participants were required to place their hands on their hips when performing the single leg hop during motion analysis. This requirement was based on the methods of Oberlander et al³² and helps control for the possibility of asymmetrical arm movement patterns that might occur due to hip weakness, particularly in the frontal plane. Controlling upper extremity movement was necessary because the upper extremities were not included in the biomechanical model used during motion analysis. Participants were then scheduled for their motion lab visit for a motion analysis of the landing phase of a single leg hop.

Motion Analysis

An 8-camera motion capture system (Vicon Motion Systems, Centennial, CO) sampling at 240 Hz was synchronized with two force platforms (Bertec Corporation, Columbus, OH) sampling at 960 Hz, to collect three-dimensional kinematics and ground reaction force data, respectively. Retroreflective markers were attached to both lower extremities and the pelvis and trunk prior to data collection. Markers placed over anatomical landmarks were used to define joint centers and segment coordinate systems (iliac crests, greater trochanters, lateral and medial femoral epicondyles, lateral and medial malleoli, first and fifth metatarsal heads). Molded thermoplastic shells with four non-collinear markers³⁶ were attached to pelvis, thigh and shank segments using neoprene wraps and Velcro.³⁷ Three non-collinear markers were attached to the heel to assess rear-foot motion. A standing trial was collected and anatomical markers were removed.

Participants warmed up for five minutes by walking on a treadmill at a self-selected pace. Participants then stretched their quadriceps, hamstrings, and triceps surae for three repetitions of 30 seconds each. The single leg hop required each participant

to hop a distance equal to 75% of their height and stick the landing for two seconds, while maintaining their hands on their waist. Participants were allowed to practice until they felt comfortable with the task, which usually resulted in three to five practice trials per limb prior to data collection. Five successful trials were collected and the process was repeated on the contralateral limb.

Hip Strength Measurements

Hip extensor and abductor maximum isometric force production was measured using a hand-held dynamometer (JTech Medical Industries, Herber City, UT) approximately one week after collecting single-leg hop data. Non-elastic straps were used to stabilize the participant and to provide resistance to the hip motion through the dynamometer.¹⁸ Two different testers participated in strength assessment, one for each group. Both testers were trained by the lead author (JT) prior to data collection. The test positions used in this study have demonstrated acceptable interrater reliability.³⁸ The order of muscle testing was randomized with the participant completing the strength measurement on both limbs before moving to the next measurement. Hip extensor strength was measured with the participant in prone with a non-elastic strap securing them to the plinth just superior to their iliac crest. The dynamometer was placed on a contoured plate (approximately 15cm X 9 cm) constructed from thermoplastic material in efforts to decrease the amount of pressure and thus minimize any discomfort related to the interface between the dynamometer and the thigh.³⁹ The inferior edge of the plate was placed 5 cm superior to the popliteal crease, and the dynamometer was secured with a non-elastic strap. The participant's knee was flexed to 90° to emphasize the gluteus maximus.⁴⁰ Hip abductor strength was measured with the participant in sidelying⁴¹ with a non-elastic strap securing them to the plinth just superior to their iliac crest. The dynamometer was placed on the contoured plate of which the inferior edge was placed 5 cm superior to the lateral femoral epicondyle and secured with a non-elastic strap. The participant was instructed to perform a sub-maximal practice trial at the beginning of each new test position for each limb to become familiarized with the procedure. Three initial trials were performed for each participant. Participants

were instructed to give maximal effort, and verbal encouragement was given to elicit optimal contraction during each trial. Each contraction was held for five seconds, with a 30 second rest given between each trial. If a participant achieved a significantly higher score on the third trial, then two to three additional trials were performed to allow the participant to demonstrate maximal strength. The highest three trials were averaged for use in data analysis.

Data Reduction

Marker trajectories data were low-pass filtered using a fourth-order recursive Butterworth filter with cut-off frequencies of 8 Hz. Kinematic data were calculated using standard rigid body analysis techniques with Visual 3D software (C-Motion, Rockville, MD). Joint angles were determined using the joint coordinate system.⁴² Joint angles were defined using the right-hand rule with flexion-extension, abduction-adduction, and internal-external rotation as the first, second, and third rotation, respectively. The landing phase, defined as the period from initial foot contact (ie, ≥ 10 N) to peak knee flexion angle, was of interest. Peak values for hip flexion and abduction/adduction angles that occurred during the landing phase were determined for each trial and averaged. Strength measures for each participant were normalized to the participant's height and weight.

Statistical Analysis

Descriptive statistics were calculated for demographic variables and single leg hop test data. Independent t-tests were used to analyze any potential differences between groups related to demographic measures and the single leg hop test. Absolute limb symmetry indexes were also calculated for both groups for the single leg hop test during the screening process. The absolute limb symmetry index (LSI) was calculated by dividing the smaller average hop distance of either limb by the larger average hop distance of the other limb and multiplying by 100%. The absolute LSI allows for between group comparisons since limbs may differ based on surgical status or limb dominance. All dependent variables were assessed for normality using the Shapiro-Wilk test. Dependent and independent t-tests were used to analyze any potential differences in maximum hip flexion and hip abduction/adduction angles and hip

extensor and abductor strength within and between groups, respectively. The limb that underwent ACL reconstruction was the limb of interest in the ACL group for between group comparisons. The limb used for statistical comparison in the healthy group was the right limb based on the fact that there were no limb differences in hop distance or hip kinematics for the healthy participants. Furthermore, all healthy participants reported their right limb as being dominant (ie, the leg used to kick a ball for maximum distance). A LSI for hip extensor and abductor strength values was also calculated for the ACL group by dividing the average strength value of the involved limb by the average strength value of the uninvolved limb and multiplying by 100%. Scatterplots were assessed prior to calculation of the Pearson correlation coefficient (r) to assess for the presence of a linear relationship and possible outliers. Pearson's r was used to assess for any potential relationships between hip strength and hip kinematics in the limbs of interest in both groups. Pearson's r was interpreted as follows: $>0.75-1.0$ = good to excellent; $.50-.75$ = moderate; $.25-.50$ = fair; and $0.00-.25$ = little or no relationship.⁴³ A $P < .05$ was utilized for all statistical analyses.

RESULTS

A total of 24 participants (12 ACL/12 healthy) met the inclusion criteria and completed the study protocol. Each group consisted of seven females and five males. Only one potential ACL participant was unable to achieve the required hop distance of 75% of their height and was not allowed to continue in the study. The healthy control group was slightly older than the ACL reconstruction group, while other demographic data and single leg hop values were similar (Table 1). The participants in the ACL group had undergone surgery an average of 32 months (range 9-58) prior to study participation. Seventy-five percent of participants in the ACL group suffered non-contact injuries, with the remaining injuries occurring via contact. Seven of the injuries occurred to the right knee and five to the left knee. The majority of participants had their ACL reconstructed using an autograft (11/12) with the vast majority of these grafts being patella tendon (10/11) and the other being hamstring tendon (1/11). The remaining participant's ACL was repaired with

an allograft tendon. Half of the ACL participants reported a known meniscal injury as well.

Strength and Kinematic Variables Within ACL Group

All dependent variables of interest met the assumption of normality. No significant differences were noted between limbs for peak hip flexion and abduction/adduction angles during the landing phase of a single leg hop (Table 2). Likewise, no significant differences were noted between limbs for hip extensor or abductor strength (Table 2). The limb symmetry index for the hip extensors was $93\% \pm 15$ and $105\% \pm 08$ for the hip abductors.

Strength and Kinematic Variables Between Groups

An independent t-test revealed that the hip extensor strength of the ACL group was statistically

Table 1. Mean (SD) of demographic variables for participants in both groups.

	ACL Group	Healthy Control	p-value (t-value, df)
Age (years)	20.8 (2.1)	23.9 (1.4)	<.001* (-4.27, 22)
Height (m)	1.68 (0.08)	1.72 (0.08)	.20 (-1.34, 22)
Weight (kg)	70.1 (6.7)	69.6 (11.5)	.88 (0.15, 22)
Single leg hop distance (cm)	167.7 (3.9)	159.7 (3.0)	.52 (0.65, 22)
Absolute LSI (%)	94.0 (3.9)	95.9 (3.1)	.19 (-1.36, 22)

ACL= anterior cruciate ligament, df= degrees of freedom, LSI= limb symmetry index.
*p<.05

Table 2. Mean (SD) of kinematic and strength variables for involved and uninvolved limbs in the ACL group.

	Involved Limb	Uninvolved Limb	p-value (t-value, df)
Hip extensor strength (N/Ht*BW)	0.18 (0.05)	0.19 (0.07)	.77 (-0.27, 22)
Hip abductor strength (N/Ht*BW)	0.30 (0.08)	0.28 (0.06)	.63 (0.54, 22)
Maximum hip flexion angle (°)	43.0 (3.4)	45.6 (2.8)	.54 (-0.62, 22)
Maximum hip abduction/adduction angle (°)	9.0 (3.2)	6.4 (3.4)	.32 (1.03, 22)

ACL= anterior cruciate ligament, df= degrees of freedom, N= newton, Ht= height, BW= body weight.

Table 3. Mean (SD) of kinematic and strength variables for participants in both groups.			
	ACL Group	Healthy Control	p-value (t-value, df)
Hip extensor strength (N/Ht*BW)	0.18 (0.05)	0.25 (0.05)	<.01* (-3.26, 22)
Hip abductor strength (N/Ht*BW)	0.30 (0.08)	0.33 (0.05)	.25 (-1.16, 22)
Maximum hip flexion angle (°)	43.0 (3.4)	51.1 (3.9)	.08 (-1.80, 22)
Maximum hip abduction/adduction angle (°)	9.0 (3.2)	0.8 (3.1)	<.01* (3.09, 22)
ACL= anterior cruciate ligament, df= degrees of freedom, N= newton, Ht= height, BW=body weight. *p<0.05			

significantly less than the healthy group (Table 3). No statistically significant difference in hip abductor strength was noted between groups. Significant differences were noted between groups for peak hip abduction/adduction angles during the landing phase of a single leg hop (Table 3). Specifically, participants in the ACL group landed with greater hip adduction. No statistically significant difference in peak hip flexion angle was noted between groups.

Hip Strength and Kinematic Associations in the Involved Limb of ACL Group

Moderate and statistically significant relationships were demonstrated for hip extensor strength and abduction/adduction angle ($r=-.62$; $p=.03$) and hip abductor strength and flexion angle ($r=.62$; $P=.03$). A fair relationship was demonstrated for hip extensor strength and hip flexion angle ($r=.40$), however; it was not statistically significant ($p=.19$). No association was demonstrated between hip abductor strength and hip abduction/adduction angle ($r=-.18$; $p=.57$).

Hip Strength and Kinematic Associations in the Uninvolved Limb of ACL Group

A moderate and statistically significant relationship was demonstrated for hip abductor strength and hip flexion angle ($r=.65$; $p=.02$). Fair and statistically non-significant relationships were demonstrated for hip extensor strength and hip flexion angle ($r=-.27$, $p=.40$) and hip extensor strength and hip abduction/adduction angle ($r=-.34$, $P=.28$). No association was demonstrated between hip abductor strength and hip abduction/adduction angle ($r=-.13$; $p=.69$).

Hip Strength and Kinematic Associations in the Healthy Group

A fair and non-significant relationship was demonstrated for hip abductor strength and hip flexion angle ($r=.39$, $p=.21$). Little to no associations were demonstrated between hip extension strength and hip flexion angle ($r=-.09$; $p=.79$), hip extension strength and hip abduction/adduction angle ($r=.15$; $p=.65$), or hip abductor strength and hip abduction/adduction angle ($r=-.17$; $p=.60$).

DISCUSSION

The purpose of this study was to analyze potential relationships between hip strength and hip kinematics during the landing phase of a single leg hop in individuals post ACL reconstruction and a healthy group of recreational athletes. It was hypothesized that both groups would exhibit significant associations between maximal isometric hip strength and peak hip kinematics during the landing phase of a single leg hop. This hypothesis was only partially supported by the fact that moderate associations were demonstrated in the ACL group, but not in the healthy recreational athletes. Specifically, a moderate and indirect relationship was present between the hip extensors and maximum hip abduction/adduction angle, while a moderate and direct relationship existed for the hip abductors and maximum hip flexion angle.

The most interesting finding was the indirect relationship between the hip extensors and maximum hip abduction/adduction angle during the single leg hop. This relationship suggests that individuals after ACL reconstruction who have relatively strong hip extensors land with less dynamic knee valgus compared to those with weak hip extensors (see Figure 1). Powers⁴⁴ has recently suggested that the gluteus maximus is capable of producing hip abduction. Fujisawa et al⁴⁵ demonstrated that the gluteus maximus was active during isometric hip abduction and the activity increased as the hip flexion angle increased. A recent study by Cronin et al⁴⁶ supports the notion that the hip extensors play a key role in minimizing hip adduction. In their study, Cronin et al similarly hypothesized that hip abductors primarily act to minimize frontal plane hip motion during the landing phase of a single leg hop followed by a cutting

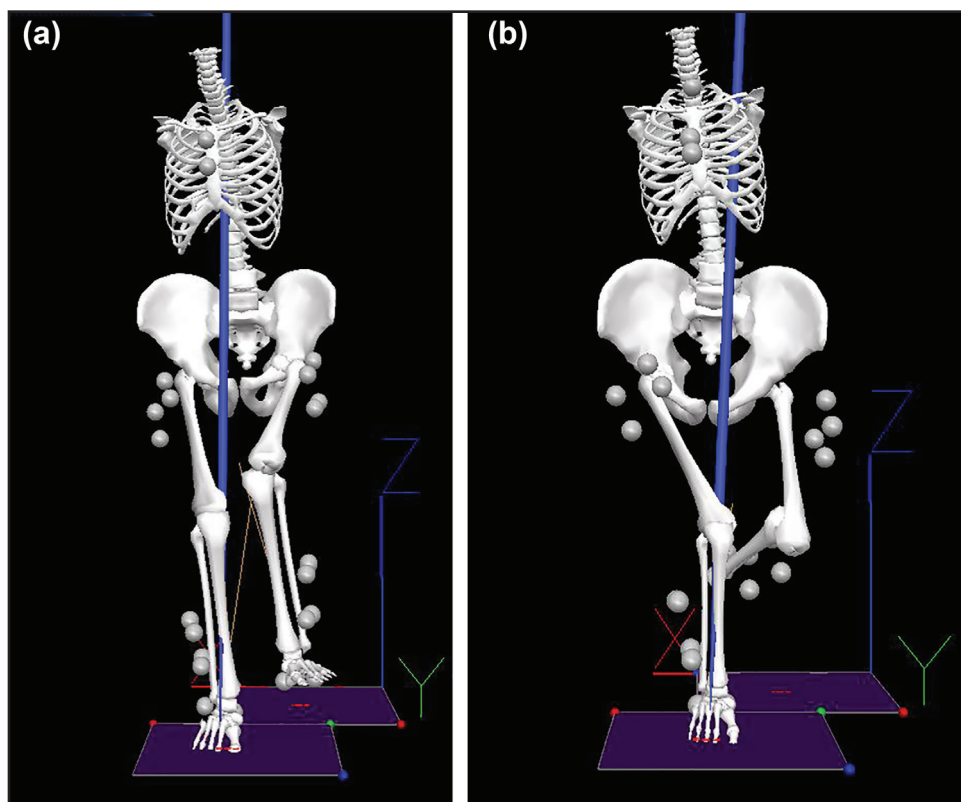


Figure 1. (a) representative landing of a participant with “strong” hip extensors and (b) representative landing of a participant with “weak” hip extensors. Note: Images sampled at maximum knee flexion.

task. Their results, however, indicated that no difference in frontal plane kinematics existed for participants who had a lower rate of hip abductor strength development compared to those with a high rate of development. They were surprised, however, to see that group differences in the rates of hip extensor strength development yielded statistically significant differences in frontal plane landing kinematics. Hollman et al⁴⁷ also demonstrated a significant relationship between hip extensor activity and frontal plane knee motion during a single leg squat. These findings combined with this study support the idea that the gluteus maximus plays a significant role in contributing to frontal plane motion at the hip and may limit excessive dynamic knee valgus.

The results also demonstrated that hip abductors were primarily associated with hip motion within the sagittal plane. A recent systematic review demonstrated only a small amount of evidence linking hip abductor weakness to dynamic knee valgus.¹⁷ The results suggest that the hip abductors may act to stabilize the pelvis in space during the landing

phase of a single leg hop as opposed to controlling hip adduction. This suggestion is based on the direct relationship seen between hip abductor strength and the maximum hip flexion angle. It might be the case that a person with strong hip abductors is able to maintain a more level pelvis thus enabling greater hip flexion to occur during the landing. Pollard et al⁴⁸ demonstrated that adolescent female soccer players that exhibited high amounts of hip and knee flexion during a drop landing task also exhibited decreased internal knee adductor moments. Therefore, increased hip flexion may also lead to less frontal plane loading at the knee joint.

Landing kinematics demonstrated that individuals post ACL reconstruction land with greater peak hip adduction angles compared to those individuals in the healthy group. The increased knee adduction differs from Trigtsted et al²⁸ who saw similar peak hip adduction patterns during a single leg hop landing between participants who had undergone ACL reconstruction compared to healthy controls. A difference in methodology may explain these

differences as Trigsted et al²⁸ had their participants hop for maximum distance. Increased hip adduction is an undesired movement pattern during a jump landing due to the decreased ability to avoid dynamic valgus collapse. Furthermore, the results demonstrated that peak hip flexion and adduction were similar between limbs in the ACL group. These results differ from those of Trigsted et al²⁸ who reported less peak hip flexion in the involved limb while peak hip adduction angles were similar. Again, this lack of agreement could be explained by differences in methodology. Typically, symmetry between limbs is a desired outcome. However, the fact that the ACL group landed with greater hip adduction compared to the healthy control group is of concern for the overall limb alignment as it relates to a potential increase in dynamic knee valgus.

The ACL group exhibited significant weakness in their hip extensors, which may partially explain the increased hip adduction seen during the jump landing. It should be noted that quadriceps weakness commonly seen after ACL reconstruction³⁰ is also another potential cause linked to the kinematic asymmetries. Recent studies have demonstrated the significant effects of weak quadriceps on landing mechanics⁴⁹ and bilateral hip extensor strength⁵⁰ for individuals who had a previous ACL reconstruction. Future studies, therefore, should attempt to perform strength measurements of all major lower extremity muscle groups in addition to measurements of trunk/core stability. In addition, body marker sets that include not only the pelvis and lower extremities, but also the trunk and upper extremities should be included in the methods to help researchers determine the influence of strength deficits on whole body movement patterns.

The other important finding is that significant associations between hip strength and hip kinematics exist in the ACL group, but not in the healthy comparison group. We are unaware of any other study that has demonstrated an association between strength and kinematics in a group of individuals post ACL reconstruction, but not present in the healthy comparison group. It could be speculated that movement strategies related to single leg jump landings likely differ in the presence of weakness. ACL reconstruction rehabilitation guidelines frequently suggest introducing

single leg landing activities as early as three to four months post-surgery.^{51,52} Therefore, individuals three to four months post ACL reconstruction likely exhibit limited variability in movement patterns during a jump landing due to lower extremity strength deficits, especially in the sagittal plane. Limited variability in movement has been suggested as a cause of injury and is therefore an undesired trait.⁵³ Limited hip strength may result in a reduced number of movement patterns and might explain why participants in the ACL group demonstrated significant associations with hip strength compared to healthy individuals. Individuals with hip weakness may rely more on ligament dominance.⁵⁴ Limited variability may also be linked to the risk of subsequent ACL injury. The results suggest that the ACL group on average had an acceptable LSI of 90% for their hip extensors. However, both limbs in the ACL group could be considered weaker when compared to the healthy control group. This finding alone highlights the importance of an increased focus on development of hip extensor strength in individuals after ACL reconstruction.

Overall, the results of this study suggest that researchers and clinicians should focus more on the function of the hip extensors, in particular the gluteus maximus, in efforts to improve lower extremity kinematics observed during sporting activities. A recent evidence-based review has highlighted the value of hip-specific neuromuscular exercise interventions that are capable of modifying dynamic knee valgus in efforts to prevent anterior cruciate ligament (ACL) injuries.¹² Recent work by Stearns and Powers⁵⁵ demonstrated that following a four-week training program which increased hip extensor and abductor strength, healthy female recreational athletes demonstrated improved landing mechanics during a drop-jump task. It remains unknown whether a similar training program would also produce improvements in landing mechanics during dynamic tasks, such as a single leg hop in individuals after ACL reconstruction.

Limitations

This study contains some limitations. First, even though the sample is representative of the general population who typically incur ACL injuries, the sample size remains relatively small. Secondly, the

sample was selected based on convenience and further limited to college-age, recreational athletes whose ACL reconstruction occurred approximately 32 months prior. Specific information related to self-reported function was not collected, but we feel that the ACL group was comparable to participants in other cross-sectional studies. Nyland et al⁵⁶ demonstrated that individuals who thought they were capable of participating in their current sport activities had an IKDC score of 87.2 on average. Triggsted et al²⁸ reported a similar average IKDC score of 88.6 for females following ACL reconstruction that were of similar age and activity level compared to participants in the ACL group. Furthermore, single leg hop distance of the females in their study was similar to the hop distance of the females who participated in this study. Therefore, we feel that the ACL group who participated in this study would have similar IKDC scores when compared to participants in both of these studies. The majority of participants in this study had also undergone ACL reconstruction utilizing a bone-tendon-bone graft. Thus, these results cannot be applied to individuals who had their ACL reconstructed with other graft sources (ie, hamstring tendon or allograft). The study design also did not allow for a uniform postoperative rehabilitation process. However, all participants did report having undergone formal physical therapy after surgery. Additionally, the influence of trunk position on lower extremity biomechanics was not assessed during a landing from a single leg hop and should not be discounted. Oberlander et al³² demonstrated that individuals who have undergone ACL reconstruction tend to demonstrate greater forward and ipsilateral trunk lean during single leg hop landings. The results of this study apply specifically to the performance of a single leg hop test, as other movements were not investigated. Finally, this study does not explain all of the variation in hip kinematics during the landing of a single leg hop. Other factors that affect landing kinematics should be studied.

CONCLUSIONS

College-aged recreational athletes who were on average 32 months removed from ACL reconstruction had decreased hip extensor strength and landed with greater hip adduction compared to healthy controls. Significant associations were demonstrated between

hip strength and hip kinematics, but only for participants in the ACL group. The results suggest that hip extensors, particularly the gluteus maximus, may serve to contribute to hip adduction, while the hip abductors may play more of a role in stabilizing the pelvis in space and may contribute to the amount of hip flexion that occurs during a single leg hop landing. Researchers and clinicians alike should consider the importance of the hip extensors in playing an important role in controlling frontal plane motion of the hip following ACL reconstruction.

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